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LEARNING FROM THE LIFECYCLE: THE CAPABILITIES AND LIMITATIONS OF CURRENT PRODUCT LIFECYCLE PRACTICE AND SYSTEMS

James A. Gopsill[1], Hamish C. McAlpine[1] and Ben J. Hicks[1]
(1) University of Bath, UK

ABSTRACT
Design teams within the High Value Low Volume (HVLV) industry are facing ever-increasing challenges in developing new products. This has been largely due to the paradigm shift towards Product Service Systems, the growing importance of demonstrating Corporate Social Responsibility and stricter environmental legislation. With the variant nature of the design process within the HVLV industry and the longevity of the product life-cycles, it is recognised that learning from previous products is essential for new product innovation and development. The ability to do this depends upon the company's product lifecycle practice and systems, and its inherent capability/limitations. To explore these issues, this paper maps typical data and information flow and the Information Systems involved, onto a generalised product lifecycle for HVLV. The map is generated from an extensive literature review and is used to critically appraise and reflect upon current product data lifecycle practice. In particular, its capability to provide design teams in the HVLV industries with sufficient data and information throughout the lifecycle phases of existing products to inform variant product design is considered.

Keywords: HVLV, Product Lifecycle, Information Re-Use

1. INTRODUCTION
The High Value Low Volume (HVLV) product industry has seen three clear trends emerging over the past decade – i) a shift towards Product Service Systems (PSS), ii) the growing importance of demonstrating Corporate Social Responsibility (CSR) and iii) ever-increasing amounts of environmental legislation. This section discusses each of these in turn before discussing the important role of data and information from the product lifecycle in meeting these challenges.

The first is known by many phrases such as Product-Service (P-S), New Service Model, Industrial Product Service System (IPS2) and more commonly Product Service Systems (PSSs). This represents a paradigm shift in business strategy with the emphasis no longer being on the 'sale of the product', but rather on the 'sale of use' of the product [1]. An example of such a strategy is Rolls-Royce's concept of 'Power by the Hour', whereby revenue is received based upon the number of hours of flight being recorded. The benefits of introducing such a strategy has been the introduction of a more stable cash flow [2], which when compared to the traditional product cash flow cycles [3], enables the company to better manage their finances.

The second trend within the industry is Corporate Social Responsibility (CSR), defined by [4] as "going beyond the interests of the firm and that which is required by law", whereby the company may be influenced by pressure from customers, employees, suppliers, community groups, governments and shareholders to meet requirements that would not necessarily provide quantifiable financial benefit to the company. HVLV companies have realised the importance of customer relations, even more so by the introduction of PSSs as the contractual agreements often span a great number of years. In addition, service contracts often generate large revenue streams and therefore securing these contracts are important to company success. For example, satisfying the customer's own values and CSR ethos is necessary to win business. HVLV companies have also realised the importance of public opinion for competitive advantage within the industry.

The third trend concerns the increasing level of environmental legislation. The issue of in-service emissions has seen constant new aims for decreasing the amount of greenhouse gasses and other pollutants being produced. This has been further compounded by public and customer opinion wishing to see a decrease in the environmental impact of the product in-service. There also exists the voluntary

European Eco-Management and Audit Scheme (EMAS), the aims of which are not to focus solely on the in-service contribution of the product but to also look into the environmental impact across the entire product lifecycle, from design, manufacture, in-service to end-of-life (EOL). Similarly, the Take-Back legislation in America, (focuses on the end-of-life stage of the product life,) aims to place greater responsibility on the originating company to take into account the disposal requirements of their product [5]. It therefore follows that pressure to reduce the environmental impact is a key consideration in new product design, and has also encouraged (or at least not hindered) the adoption of PSS strategies. This is because asset-ownership remains with the company and thus any improvements to in-service performance will more directly contribute to the profit potential of the product over its life.

1.1 Importance of Data and Information

The study of data and information use in design teams has highlighted various areas that require further research. For example, interviews conducted by [2] revealed that representatives of an HVLV company believe that knowledge and information management is essential for better decision-making. In addition, [6] presents a case study on a knowledge-sharing network, showing its ability to increase productivity, whilst [7] explores the effect of communication on productivity and lead-time. [8] demonstrates that data and information remains in a company for many years longer than any other item and thus must hold value by virtue of not being disposed of or deleted. The importance of the right information of the right amount has also been discussed by [9], who concludes that there is an inverted u-shape result in the absorptive capacity of information of a designer/design team – that is, there is an optimal amount of information, with too much information, at the wrong time or in the wrong format being difficult to manage and possibly impacting on the ability of the designer to make an optimal decision.

It has been accepted that traditionally, the committed cost is approximately 70% at the design phase [10, 11]. However, it can be argued that with the additional responsibilities being imposed on the company for the in-service operations and the EOL disposal of the product, the committed cost will increase. This further highlights the importance of designers being able to make the right decisions at the design phase to be able to meet the additional challenges of PSS, CSR and environmental legislation previously discussed and thus to commit cost pertinently. Whilst there are many examples of data and information generated during the in-service phase being fed-back to the designers, this paper focuses on exploring whether design team could re-use, more effectively the huge amount of data and information generated from previous products across the their lifecycle. This includes the use of data and information from design, manufacture, in-service and EOL of existing products to support design of variant products.

To explore this issue, this paper develops a generalised product lifecycle and also maps the processes that generate data/information, together with the information systems used to store and manage this data/information. The resulting map will be used to provide an insight into the current capabilities and limitations of the systems used within the product lifecycle to assist designers in meeting new design challenges created by PSSs, CSR and environmental legislation. It will also be used for an explorative study into what information is currently available and what information could be potentially useful to design teams. The current potential and key future research challenges are also discussed.

2. METHODOLOGY

The methodology used in the creation of the map of data and information flow through the product lifecycle is depicted in Figure 1. Flow is used here to encompass the common data/information activities and tasks such as, capture, use, reuse, storage and management. The approach is similar to reviews conducted by [1], whereby a comprehensive literature review has been conducted using a selection of key terms relating to the specific study. As in [12], the review presented in this paper has covered a large range of journal databases to provide the breadth required for such a large research space. The literature review includes approximately 150 sources, consisting of journal articles, conference proceedings and textbooks; with a majority of the papers used being review papers, such is the scope of the space being investigated.

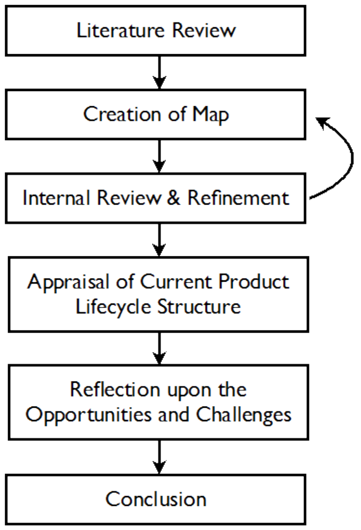

Figure 1: Methodology

From the literature review, the initial creation of the generalised product lifecycle (alongside the information flow through the lifecycle) is created via an iterative approach. The map is then used to critically appraise the current capabilities by providing a visual assessment of the data and information flows through the product lifecycle and the systems that influence these flows. After this appraisal, the opportunities within the current lifecycle are discussed, alongside the challenges facing the introduction of methods by which data and information could be fed back to design teams without altering the current ICT infrastructure of the company. Finally, the study concludes by highlighting the key opportunities that could be exploited and the possible future directions for continued research for feeding information back into the design phase of the lifecycle through more radical changes to IT infrastructure and capability.

3. MAP DEVELOPMENT

Following multiple iterations during the literature review phase, the final map is presented in Figure 2, with the key contributing papers in the development and formation of the generalised HVLV product lifecycle presented in Table 1, and associated list of acronyms contained in Table 2. The map evolved into a circular design to highlight the variant and cyclic nature of HVLV product design, and, also to show the incorporation of in-service and EOL stages of the product lifecycle with regards to the parent company. However, it is noted that the product lifecycle is not a complete cycle, rather it is a goal that companies are striving to achieve - thus there is a gap between the beginning and end of the product lifecycle. During the literature review, it became clear that there was a requirement to provide levels for the various systems and processes that interact and handle data and information through the product lifecycle. To clarify the data and information flow through the product lifecycle, three levels were identified. The first level depicts the tools, tasks and methods that generate, capture and utilise data and information within the product lifecycle. The second represents the data and information generated from within that particular phase of the product lifecycle, and the final top level of the structure concerns the enterprise wide systems that have been put in place to manage the data and information. The divisions between the various phases do not extend to the highest level due to the enterprise wide systems often being involved in the management of data and information from various lifecycle phases. However, the systems have been placed at the stage of the product lifecycle where they are most influential.

Table 1: Key Contributions to the Development of the Generalised Product Lifecycle

Contribution	Reference
Stages of the Product Lifecycle	Thimm et al [13]
Stages of the Design Process	Pahl et al [14]
Stages of the Product Lifecycle alongside the PLM Strategy	Hassan et al [15]
Stages of the End-of-Life Product Lifecycle	Sudarsan et al [16]
Design phases of an HVLV product	Ferguson and Browne [17]
Highlighting the overlapping and merging nature of the phases within the product lifecycles	Asiedu and Gu [10]
Tools & Tasks associated with in-service maintenance	Garg and Deshmukh [18]
Defence availability contract CADMID cycle	Bankole et al [19]

Table 2: List of Acronyms within the Model

Design Phase	Detailed Design / Freeze
PLM - Product Lifecycle Management PDM - Product Data Management EDM - Engineering Data Management CAD - Computer Aided Design FEA - Finite Element Analysis CFD - Computational Fluid Dynamics QFD - Quality Function Deployment FMEA - Failure Mode and Effects Analysis FMECA - Failure Modes, Effects and Criticality Analysis CAM - Computer Aided Manufacturing DMU - Digital Mock-Up PP - Process Planning FTA - Fault Tree Analysis	CAPP - Computer Aided Process Planning BOM - Bill of Materials
In-Service Operations	**Manufacture**
NDT - Non-Destructive Testing EHM - Engine Health Monitoring SHM - Structural Health Monitoring CM - Condition Monitoring MRO - Manufacturing, Repair and Operations PM - Preventive Maintenance CBM - Condition Based Maintenance TPM - Total Productive Maintenance CMMS - Computerised Maintenance Monitoring Systems ECM - Effectiveness Centre Maintenance SMM - Strategic Maintenance Management RBM - Risk Based Maintenance VBM - Vibration Based Maintenance TMM - Total Maintenance Management MMIS - Maintenance Management Information Systems	ERP - Enterprise Resource Planning MRP - Manufacturing Resource Planning MPM - Manufacturing Process Management RFID - Radio Frequency Identification SCADA - Supervisory Control and Data Acquisition CAM - Computer Aided Manufacture SCM - Supply Chain Management TQM - Total Quality Management

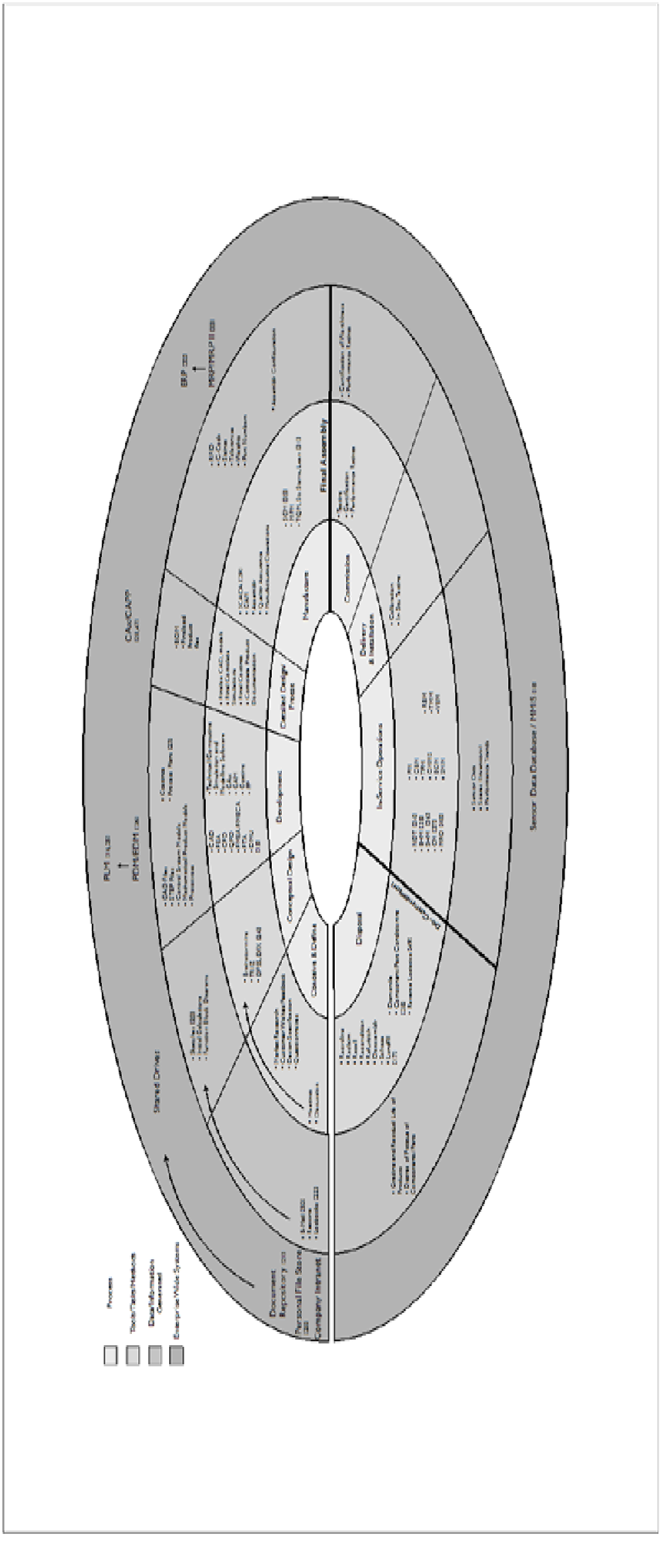

Figure 2: Data and Information Flow Map

4. CURRENT CAPABILITY

It is widely recognised [21,39,40,50] that there are processes and systems (such as a company's intranet) that are in continual use throughout the entire product lifecycle. To highlight this fact, these systems, tools/tasks and the resulting data/information generated have been placed at the beginning of the diagram and arrows have been used to show the continual use of these systems/processes throughout the product lifecycle. With these systems in place, other key systems mentioned within the literature can be classified. These are now for summarised each main phase of the lifecycle.

During the conceptual design phase, small teams of design engineers are involved in the development of the new concepts of variant HVLV product. In most respects when compared to the data/information flow of the rest of the product lifecycle, the conceptual design phase can be seen to be the most unstructured and organic, involving the use of sketches [23], various meetings and consultations with engineers across the entire product lifecycle, and initial calculations [40]. Due to the often informal and unstructured nature of the data/information generated in so many different formats, shared network storage are often used within this phase of the lifecycle to manage the data and information for the design team, together with paper-based sources such as sketches and the output of brainstorming sessions. Some of these sources may not be managed in any formal system. Rather, they are under the control of the individual and not accessible to the wider team [20, 51-52].

Moving to the development phase of the product lifecycle, a more formulated and structured data and information flow is revealed. At this point, a very large data and information set is created due to the high complexity of the design of HVLV products, and the sophisticated nature of the analysis tools at the disposal of the engineers. The original systems developed to handle the data generated (and in particular the CAD geometry files) were introduced to ensure that assemblies were up-to-date, and also enabled the checking of clashes and tolerance issues. Known as Engineering Data Management (EDM) or Product Data Management (PDM), these systems were introduced in the 1980s [26] and have now been extended to encompass the management of manufacturing, in-service and EOL data and information. The common terminology for this system is Product Lifecycle Management (PLM). Although the ideology for such a system is to be able to manage the data and information across the entire lifecycle, the literature review has indicated that PLM still resides firmly within the design phase of the product lifecycle. However, the trend is that such systems are attempting to integrate CAD and CAM functions [16,25,48].

However, continuing through to the manufacturing side of the HVLV industry, there emerges a competing data/information structure. Enterprise Resource Planning (ERP) was introduced in the 1990s to extend the capabilities of the Manufacturing Resource Planning (MRP) systems [32,33]. As with the development phase of the design process, the manufacturing phase contains many processes, tools and tasks that generate and use information from within the manufacturing area. Its key focus has been upon the management of finances, human resources, operations & logistics (i.e. SCM), sales & marketing. Although PLM and ERP were developed from different perspectives, their goals of providing a method for structuring and managing the data and information flow to ease and support the processes, tools and tasks are the same. Thus, there are sometimes no clear boundaries between them, leading to potentially duplicated information and costly interfacing issues.

Due to the arrival of the previously discussed challenges affecting the HVLV industry, the importance of managing the data and information during the in-service and EOL phases is now becoming critical. Although currently in their infancy when compared to the more established PLM and ERP systems, current literature reveals that database systems are in place for the storage of the data and information from these phases. However the access and use of in-service information appears to be mainly utilised in the maintenance and performance monitoring fields [18]. The full extent by which the data and information from in-service and EOL can be utilised has yet to be fully realised. For example, great numbers of maintenance reports are generated and have already been a source for an initial trial in feeding back product lifecycle data back to design [41,53], albeit just by providing access to the repository and basic statistical analysis (3300 maintenance records were used in the study). In addition, customers, suppliers and/or third parties often hold the in-service and EOL data and information and this can lead to information transfer issues.

To summarise, it can be seen from the literature and resulting map presented in Figure 2 that the development of the systems has been heterogeneous and they have been put in place to serve a specific purpose, with their capabilities extended over time as new challenges have emerged. This paper argues that there is potential in exploring how the vast quantities of data and information from the entire lifecycle may be exploited more effectively for purposes other than its original intended use. Potential opportunities and challenges in doing this are now discussed for each main lifecycle stage.

5. OPPORTUNITIES AND CHALLENGES

Considering Figure 2, it is apparent that the product lifecycle of an HVLV product generates large amounts of data and information in a great number of formats (for example, [21] analysed a 38,500 file portion of a shared network drive). As this is a generalised map created from the literature, there are likely to be even more proprietary systems, processes and tasks generating and using data and information, especially in HVLV industries. This paper also contends that the data and information captured by these formal enterprise-wide systems represents only a small fraction of the total amount of data and information that could be generated and captured. Further, whilst Figure 2 focuses on the data and information, which is produced by the product lifecycle, there is a potentially a large amount of data and information that is being received and used by engineers that is not generated by the lifecycle (e.g. Online Engineering Knowledge Bases and Academic Papers). The challenge is thus, how can the data and information captured (and generated but currently not systematically or formally captured) within the lifecycle assist designers at the early phases of design? Opportunities to do this at each stage of the lifecycle are now identified in sections 5.1 to 5.4 and discussed with respect to what could be achieved with minimal change in the current ICT structure of the company. Key challenges that need to be overcome are then discussed in Section 5.5.

5.1 End-of-Life

From the activities performed during the EOL phase of the product, a great deal of data and information is generated regarding the residual life and condition of components and parts. Analysis of this data and information could reveal trends indicating which parts or components are critical in determining the operational life of the product and how parts have performed when compared to the original specification. In light of this analysis, design teams have the opportunity to focus their attention on the critical parts of the product and reduce the time spent attempting to optimize components that may have little bearing on the life or performance of the product. Also, the analysis of disassembly and recycling reports could indicate trends concerning the disassembly of the product, including the components/parts that have the greatest environmental impact. From this information, design teams can have a greater understanding of the issues arising during EOL disassembly and thus focus on these issues for the subsequent design. The above concepts aim at reducing time taken during the design phase, reduce time at the EOL for disassembly and to also optimise the residual life contained within the parts of the product.

5.2 In-Service

In-service activities provide potentially the greatest amount of data and information due to the sensor data and user feedback that could be captured. For example, a typical flight recording can amount to a 1GB sensor data file [42]. This sensor data has the potential of providing a great deal of useful information to design teams through novel data mining techniques. One such application are the use of mathematical models of the product generated during the design phase to predict the performance characteristics of the product and are often used to monitor the performance of the product during in-service operation. However, it could be possible to use in-service data to create a real-world model of the product, whereby comparison of the original model can be performed, potentially in real-time This would inform design teams on how well the model created in the initial phase relates to the actual product ‘as used’ and enable design teams to understand whether the assumptions made are valid. Thus upon the next design, this information could be fed-back to enable a more accurate initial model to be developed and product specification based upon actual usage statistics. There is also additional potential in the sensor data as it may provide an understanding on how various parts and components within the HVLV product are performing in-service. From this information it would be possible to assess which areas of the product are performing above/below specification and thus for the next generation products, design teams can use this information to focus upon the areas which require improvement. A final potentially interesting challenge would be to automatically, systematically and pro-actively analyse maintenance reports for trends in issues being raised (and difficulties in maintenance of the product), which could be used by design teams to improve the accessibility and alter component design to avoid issues recurring.

5.3 Manufacturing

During manufacture, a wealth of data and information is generated on the sourcing, availability and allocation of materials/parts. Again, systematic and pro-active analysis of this data and information could provide potentially useful information on common delays with parts/materials and the feeding of this information back into design could aid in redefining the materials and parts used to avoid delays within the supply chain. Manufacturing systems and procedures also record the sizing, tolerances, weights and positions of parts within the product and could be also provide a useful source for aggregation analysis. These values could be used to provide trends in the performance of the manufacturing systems and indicate where there may be issues in tolerance build up, weightings or balancing of components. These trends could provide design teams with the information they may require to redesign the stages of manufacture to prevent issues re-occurring.

Further, the combination of manufacturing and in-service data could provide a very useful insight into the performance of the product. Using in-service data, development of 'good/bad' models of the product could be produced and from this grouping, trends in the component values could be analysed. These trends could then be fed-back to design to highlight key tolerances, sizings and weights that are required for a 'good' product and also the components, which do not require such stringent tolerances.

5.4 Design

As mentioned previously, design contains the greatest variety in the types of data and information generated and a great deal of information is verbally communicated through meetings [43]. However, such informal information could hold potential for feeding back useful information to design. The analyses of e-mails, meetings and report structures could reveal patterns and be used to formulate a 'good/bad' model for the design process. A logical argument is that successful products may have common patterns within the design process and the isolation of these patterns could create a 'good' model for the design process. This may have the ability to aid management of the next product design and although each design is inherently different, the patterns produced could provide useful guidance when one considers the entire lifecycle of an HVLV. Also, designers use many personal stores of data and information, and providing the ability to identify and highlight potentially useful information within personal stores may enable increased productivity and creativity within the design process.

5.5 Challenges

It was noted earlier that the systems currently in place within the generalised product lifecycle have been born out of necessity and have often developed in an ad-hoc and relatively unstructured manner, sometimes over a period of decades. Also, the PLM and ERP systems in place are currently much more capable systems in comparison to the in-service and EOL phases. This is understandable due to the relatively recent inception of in-service and EOL into the industry model. [40] characterises the requirements of engineering information systems and reveals that designers in different roles require access to and use different data and information systems to solve the problems they face. The study also cites [44], which indicates that designers spend significant amounts of time (up to 30%) searching for and accessing information. In addition, [45,54] has raised the issue that the cost of finding useful information may be inhibiting the use of product lifecycle data and information. Indeed, the literature review and in particular, a study by [17] focused on the EOL stages of the lifecycle highlighting current lack of support for data and information flow through the different systems within the product lifecycle.

Finally, a collaborative design study [11] discusses the 'fuzziness' of the data and information used during the design phase and notes that traceability of these sources can be difficult when drawn from many different sources and existing in many different formats. Such fragmented systems are likely to hinder the retrieval and analysis of information, and therefore be likely to inhibit the optimal use/re-use of information from the lifecycle and could also contribute to information overload [46]. In addition, it has been highlighted that there is a wealth of information residing within personal stores, which places further complications on data and information retrieval, particularly within the design phase.

In summary, the appraisal of the lifecycle map presented in this paper has revealed that enterprise wide systems hold a wealth of data and information that could be accessed and fed-back to designers in a much more comprehensive way than that is achieved at present. Through the mapping of the product lifecycle, this study has identified a number of potentially interesting opportunities, all of which follow a common trend and have a common aim: To process the large datasets available within the enterprise wide systems in an automatic, systematic and pro-active way to identify trends and to present the information in a useful, condensed manner. There also emerged four key challenges: i) The need to access and index, the data and information stored by the current enterprise wide systems, ii) the identification of useful personal information and its transformation to group information, iii) the development and utilisation of tools that enable pattern discovery/identify trends and iv) the creation of innovative visualisation techniques to present the information to the recipient in a manner that does not lead to information overload. Meeting these challenges would enable the information needs of designers to be met more effectively and in turn allowing them to meet the new design challenges posed by PSS, CSR and environmental legislation.

6. CONCLUSION

This paper has considered the opportunities and challenges of the feeding back of information from previous product life-cycles to aid design teams of new variant High Value Low Volume products. This is an increasingly important topic, due to the new challenges introduced by Product Service Systems, Corporate Social Responsibility and increasing environmental legislation. By conducting an extensive literature review, a generalised product lifecycle has been developed and the current data and information flow has been mapped. The map identified 68 tools/tasks and eight enterprise systems used to manage, utilise and store the indicated hundreds of thousands of data and information files generated within the product lifecycle. This map was used to critically appraise and reflect upon the opportunities for – and challenges of – feeding back information to design teams. These all followed a common trend: The need to *automatically, systematically and pro-actively* process the large datasets made available by the enterprise wide systems to identify trends and present the information in a useful and condensed manner.

In addition, the challenges currently facing these research opportunities was discussed, with four key issues being raised. i) The need to access and index, the data and information stored by the current enterprise wide systems, ii) the identification of useful personal information and its transformation to group information, iii) the development and utilisation of tools that enable pattern discovery/identify trends and iv) the need to create innovative visualisation techniques to present the information to the recipient in a manner that does not lead to information overload.

6.1 Future Direction

The authors are continuing their research into identifying the current capabilities and limitations in the capturing and re-use of engineering knowledge, data and information throughout the entire product lifecycle. One of the fundamental challenges to emerge is the capturing of informal information and its potential in integrating and completing design records to enable more effective re-use and enable the application of knowledge discovery techniques.

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Contact: J.A. Gopsill
University of Bath
Department of Mechanical Engineering
Bath, BA2 7AY
United Kingdom
Tel: Int +44 1225 386131
E-mail: J.A.Gopsill@bath.ac.uk

James Gopsill is a postgraduate researcher in the Department of Mechanical Engineering at the University of Bath. He has continued his studies at the University of Bath after receiving a first class MEng (hons) degree in Aerospace Engineering. His current interests include the capturing and re-use of engineering knowledge, and the application of knowledge discovery techniques on data and information.